

## PERFORMANCE OF THE UPGRADED ORRORAL LASER RANGING SYSTEM

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## 1. Upgrade Arrangements

An Agreement 'being in respect of a project to develop Laser and Control Systems Upgrade to Orroral Laser Ranging System' between Electro Optic Systems Pty.Ltd. (EOS) and The Industry Research and Development Board (IRDB) of the Commonwealth Department of Industry, Technology and Commerce was signed on 23 March 1990. On the same day, a corresponding 'Agreement for Collaborative Research and Development of Laser and Control Systems Upgrade to Orroral Laser Ranging System' between the Australian Surveying and Land Information Group (AUSLIG) of the Commonwealth Department of Administrative Services and EOS, was signed. Under these Agreements, the research and development costs were shared between the three parties according to a standard IRDB formula, with AUSLIG having the option to purchase the prototype for its residual value upon successful demonstration. IRDB involvement was directed towards fostering export-oriented Australian high-technology industry.

The old system was de-commissioned on 6 March 1991, although preparatory work such as moving the laser and installing the heads and capacitor banks necessary for conversion to Active-Active mode was completed prior to that date. LAGEOS I was acquired a month later, on 10 April, and AJISAI on 12 April 1991 in Orroral's first-ever attempt at a 'low' target. The following eight months were spent in debugging and refining the new system and preparing for the ill-fated attempt to measure the geodetic baseline between the Orroral Laser Ranging System (OLRS) and the Saudi Arabian Laser Ranging Observatory (SALRO) set up at the Canberra Deep Space Communications Complex, Tidbinbilla to complement terrestrial and GPS surveys and to link SLR at Orroral with VLBI at Tidbinbilla.

The upgraded OLRS was deemed by AUSLIG to be operational from 1 January 1992, and final payment to EOS for purchase of the residual prototype was made in June 1992. A contract for software maintenance and further development was awarded to EOS in November 1992.

## 2. System Prior to 1991

The original system was the Orroral Lunar Laser Ranger (LLR), lent to the Division of National Mapping (Natmap) in 1973 under a Memorandum of Understanding involving NASA, Smithsonian Astrophysical Observatory and US Air Force Geophysical Laboratory. It was upgraded to include ranging to artificial

satellites under a contract from NASA signed in 1981, the first returns from LAGEOS-I being acquired in mid 1984. Some verified returns from the moon were received in 1985, and ranging to ETALON I & II started in 1990. It was not really possible to expect results for two-way ranges less than 35 milliseconds, which is one of the main reasons for embarking on the upgrade being described here.

Note : Natmap was merged with another Commonwealth agency in August 1987 to form AUSLIG.

DOME : The 9 metre diameter hemispherical dome by Ash Domes of Plainfield,IL was installed atop the original cylindrical Observatory building in 1973. Its AC motors for rotation during observing were manually controlled by a Left-Off-Right lever.

TELESCOPE : 1.5 metre aperture Ritchey-Chretien reflecting telescope, optics by University of Arizona. The tailpiece at the Cassegrain focus carries an eyepiece mounted on an X-Y stage for star observations and to facilitate offset guiding for lunar ranging.

The telescope is used both for transmitting and for receiving. It is depicted in figure 1.

TELESCOPE MOUNT : The telescope tube is by Astro Mechanics of Austin,TX. The original equatorial mount was replaced in 1981-2 by an X-Y ("alt over alt") mount by Contraves, and a Coude Path and the Contraves MPACS drive and readout systems were added. The drive accuracy is better than 0.002 degrees and encoder resolution is 0.0001 degrees.

An interface/controller was built, and all interface drivers and control and mount modelling software were written, by Natmap.

COUDE PATH : The Coude path incorporates a Matching Assembly consisting of two lenses whose combined focal point coincides with the focal point of the telescope. These lenses are in the East bearing of the telescope's inner axis. The Coude path connects the telescope with the laser, transmitter and receiver assemblies which are mounted on Newport optical benches in environmentally stable rooms. A Times 5 Beam expander by Special Optics,NJ on the Coude bench expands the transmitted beam prior to injection to the telescope through mirrors in the North bearing.

TRANSMIT/RECEIVE ASSEMBLY (T/R) : A rotating aluminized mirror with two holes in it, co-rotating 'dogbone' holding two ND filters and CAMAC-controlled stepping motors constituted the T/R assembly purchased from McDonald Observatory,TX in 1983. Laser firing was triggered by optically sensed notches in the rim of the rotating mirror.

The mirror was replaced in 1987 by an 'Appler mirror' in which the holes were just glass left uncoated (glass-hole), and which permitted positive, unambiguous ranging to a ground target and,

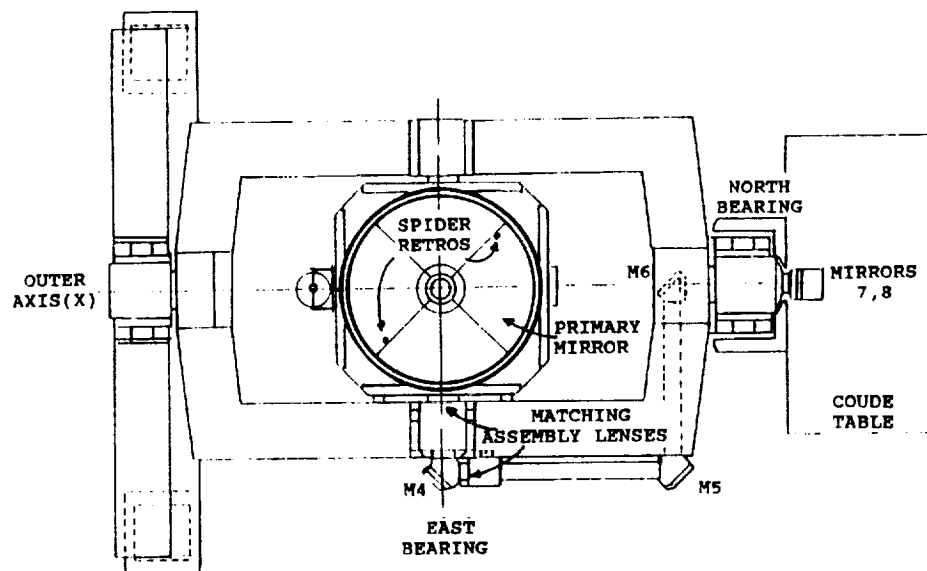
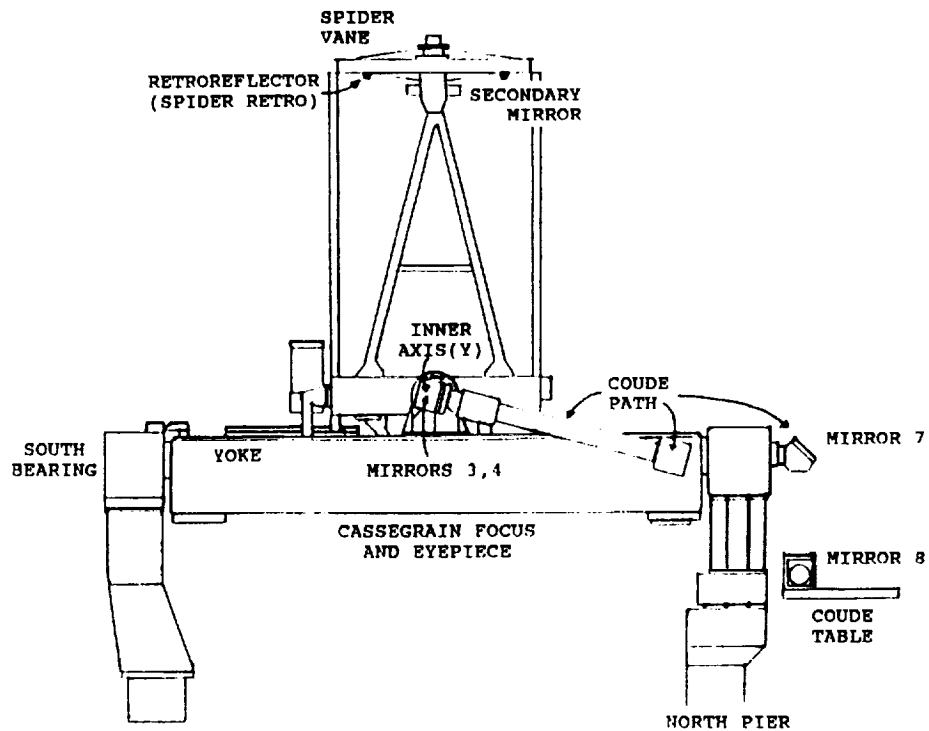


Figure 1: Orroral Laser Ranging System telescope - elevation and plan. (Derived from Contraves 'NLRs Telescope Manual'.)

for real-time internal calibrations, to geodetically accessible retro-reflectors placed on the spider vanes holding the telescope's secondary mirror.

The interface was controlled by the CAMAC bus system, and driver and high-level software was written by Natmap in collaboration with the University of Texas.

RECEIVER/DETECTOR : A light-tight box containing a turret of 5 pinholes (spatial filters), a turret with a  $10\text{ A}^\circ$  filter and a hole, focussing optics and detector mount was provided by McDonald Observatory. The detector mount was replaceable by an eyepiece for star alignments.

The detector was an RCA 31034A PMT until 1986, when the first of a series of ITT F4129f z-plate MCP PMTs was installed.

LASER : A Quantel YG 402 DP Nd:YAG laser frequency doubled to 532nm output wavelength was purchased as part of the 1981-3 upgrade. Its Q-switching and pulse slicing were accomplished passively, the mode locking being active/passive. Two amplifiers combined to produce in excess of 250mJ per pulse at ten pulses per second when needed. The pulse slicer was replaced by a Quantel solid-state slicer model SPS411 in 1987.

The laser was removed from its Quantel plate in the Coude room and relocated to an RF-shielded room one floor lower in the Observatory building in August 1990. Its components were bolted directly to a Newport optical table.

[The original Hughes 6943A<sup>0</sup> ruby laser of the Orroral LLR prior to 1981 was bolted to the side of the telescope tube.]

LASER RANGING CONTROLLER (LRC) : This main interface/controller was designed and built by Natmap. It set windows and gates, controlled laser firing, and managed the epoch timing system.

EPOCH TIMING SYSTEM : Range measurements were accomplished by measuring the 'epoch' (time of day) of separate events, rather than depending upon a Time Interval Counter. The LRC time base was driven by a high spectral purity Oscilloquartz 2200 quartz frequency standard at 10MHz, and its clock synchronised at the start of each pass to an external Hewlett-Packard caesium beam frequency standard whose own clock was kept within 1 microsecond of UTC. The LRC Clock was used to time tag events to 100 nanosecond resolution.

Each laser shot produces at least three events to be time tagged: start diode pulse, internal calibration pulse from MCP/PMT, and one or more satellite returns from MCP/PMT (the quest to detect more than one 'satellite' return per shot was abandoned in the mid-1980's). The epoch timing system philosophy theoretically enables many events to be recorded per shot using identical equipment, limited only by instrumental reset/read times.

Two channels were used in practise to obtain fine resolution, one for start diode and one for MCP/PMT. Each comprised a separate channel of the Tennelec 454 Quad Constant Fraction Discriminator (CFD), a LeCroy 4202A Time to Digital Converter (TDC), and a pair of 8-channel LeCroy 2228A TDCs as verniers covering different 50ns sections. The 8 78-picosecond resolution channels of each 2228A were majority voted and meaned to improve resolution to about 28ps. A standard calibration routine was run with each pass to relate the intrinsic 2228A delays to each other, with the scale factors being calibrated periodically against the 4202A TDCs.

All TDCs were read via the CAMAC bus system. Software for these tasks was written by Natmap.

RECEIVE ENERGY MONITOR : A LeCroy 2249A Analog-to-Digital Converter (ADC) ('charge digitiser') was installed on the MCP line in March 1990. It is controlled and read through the CAMAC bus system, and is gated by the 'AND' of the range gate window and of the discriminator output pulse delayed appropriately. Its input signal is amplified by a Stanford Research SR440.

OPERATING SOFTWARE : Apart from the lunar prediction package based on EULER and the satellite prediction package based on IRVINT, which were imported with the aid of Randall L. Ricklefs, all interface drivers, control and operations software, predictions, post-processing, mount modelling, simulation and test software was written by Natmap.

SYSTEM CALIBRATION : Until the end of 1987, the internal calibration pulse was picked off each transmitted laser pulse by a minutely reflecting 'feedback plate' in the T/R box and fed to the MCP/PMT through ND filters in the co-rotating 'dogbone'. The optical and electronic delays between this feedback plate and the epoch timing system were thus well calibrated, but the delay between the feedback plate and the system reference point was not well known, so it was not possible to assess system accuracy properly as it was found impossible to measure or even estimate the length of the convoluted Coude path (with its five refracting elements as added complications) to better than 10cm.

The advent of the 'Appler mirror' in 1987 made it possible to range to the 'Spider Retros' simultaneously with distant targets. The effective reflection points of the retro-reflectors were related to the instrumental reference point and external survey marks early in 1988 with 3mm accuracy by precise survey, enabling accurate correction constants to be calculated.

A ground target was installed at a distance of 1.1km across a valley in November 1987, and surveyed in along with 'Spider Retros'. A session of ranging to this target accompanied each LAGEOS-I pass, and provided a check on the accuracy of the correction constants referred to above. It is also invaluable for assessing such things as the effect of signal strength on range accuracy and the actual precision obtainable at any given time.

### 3. Elements of the Upgrade

DOME : Automated rotation was provided through hardware and interface controllers. Two DC variable-speed motors were installed in 1991 and new variable-speed controller, interface and software are now under development.

TELESCOPE and COUDE PATH : Not affected by the upgrade.

TELESCOPE DRIVE : A new interface/controller for the MPACS, and corresponding interface driver and high-level software, were provided, as were two new handpaddles with their interface, controller and driver.

TRANSMIT/RECEIVE ASSEMBLY : A completely new box was provided (figures 2,3). The T/R mirror has two genuine holes, and is connected to the co-rotating 'dogbone' by a shaft incorporating a clutch unit. Rotation rates up to 20 revs/second are possible, and are controlled directly from the MRCS. Laser firing is triggered by notches on the T/R mirror rim as before. Laser fire commands may be inhibited through a 'divide by' facility so that only every first, second, third or fourth notch actually causes a shot.

A minutely-reflecting wedged feedback plate (FBP) directs part of the transmitted pulses to targets on the Coude Table for the optical calibration of the timing system and, optionally, for a real-time internal calibration target ('Table Target'). The wedge also reflects a small part of return pulses through ND filters in the 'dogbone' to the detector; this facility is routinely used for the spider retro and ground target returns, the bulk of whose energy passes back through the T/R hole and is lost. Such returns therefore traverse a different path inside the T/R box than do satellite returns which take 1.644ns longer.

An electrically controlled PLZT optical attenuator is placed between the feedback wedge and the 'dogbone' to aid in matching calibration and ground target signal strengths to satellite return signal strengths. A special circuit ('wobulator') can sweep through the voltage range with 3 second period to give varying energies when adjusting discriminator walk.

RECEIVER/DETECTOR : A new Receiver Box (figures 2,4) contains a new 4-pinhole turret, separate ports for MCP mounting (with 10A<sup>0</sup> filter built in) and eyepiece/RCA PMT mounting, a flip mirror to switch between ports, a flip mirror to access a CCD camera, a LED pulser to aid MCP characterisation, and new focussing optics. The flip mirrors can be software controlled via the MRCS.

To date, only ITT F4129f MCPs have been used, while the CCD camera and LED Pulser have not been used at all.

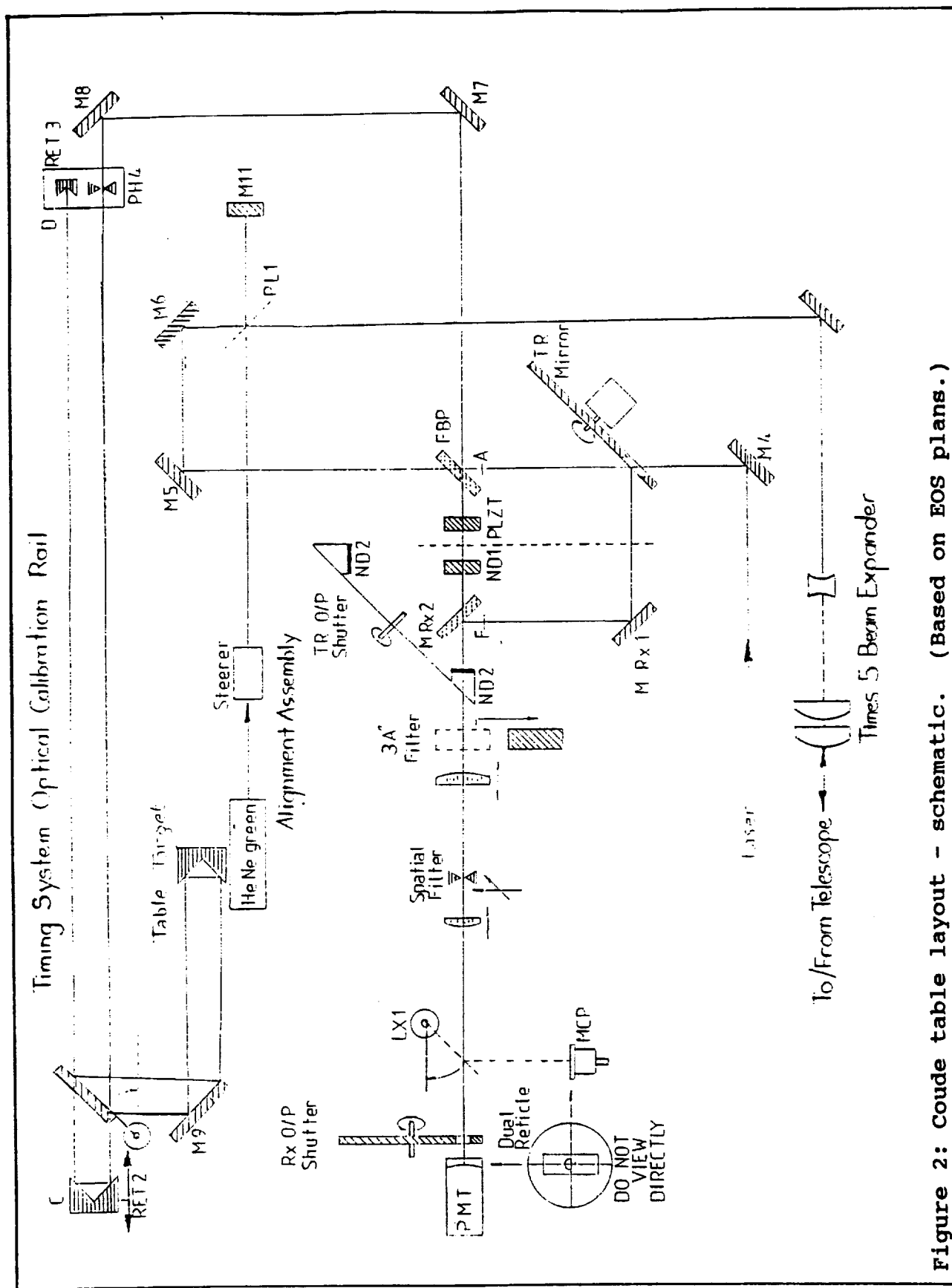


Figure 2: Coude table layout - schematic. (Based on EOS plans.)

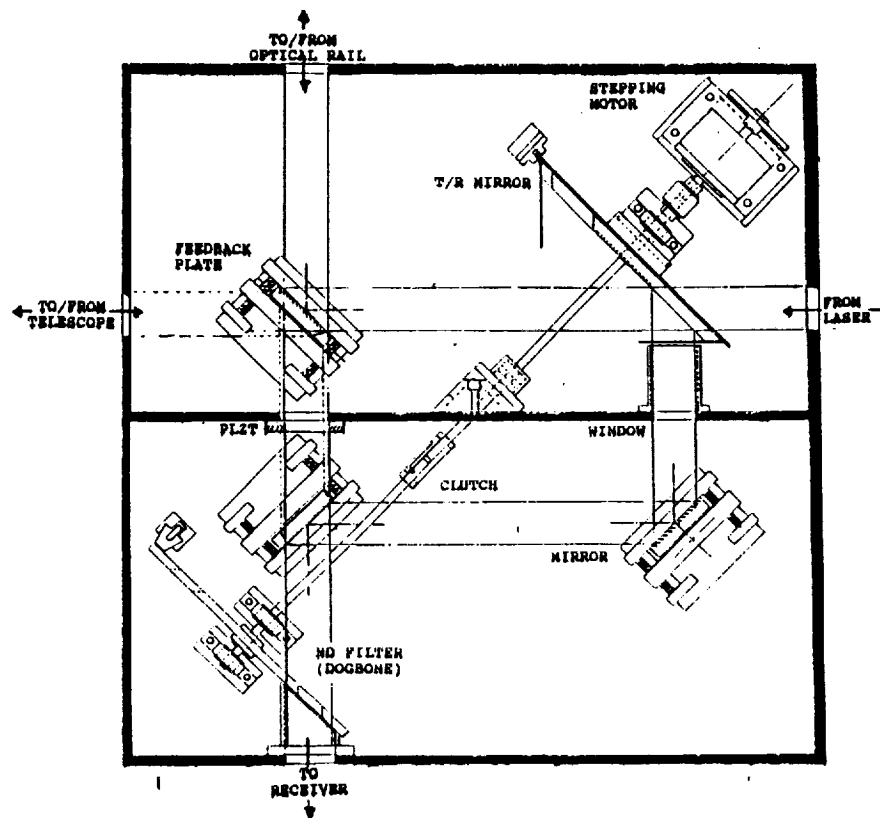


Figure 3: EOS Transmit/Receive assembly. (From EOS drawings.)

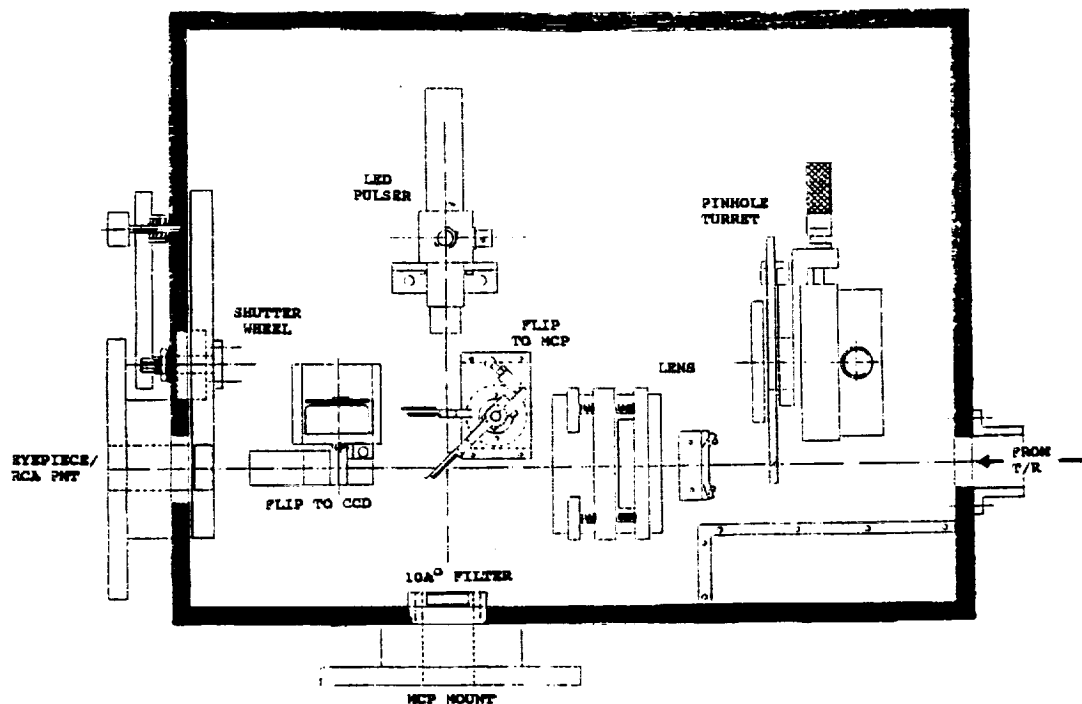


Figure 4: EOS Receiver assembly. (From EOS drawings.)



LASER : The oscillator was converted to Active Q-switching, Active mode-locking to a design by the Centre for Laser Physics of The Australian National University licenced to and developed by EOS. The SPS411 is also connected to the Active-Active circuitry to give positive pulse selection.

It was found necessary in 1990 to replace the laser heads with high-efficiency heads, and the capacitor banks with new units having simmer circuits. This work was supported by IRDB and completed in January 1991 with the installation of a CB632 and two CB631 units, and SF606-4, SF611-07 and SF611-09 heads, all made by Continuum. Later, a Continuum MV 70 RF generator for the Acousto Optic Modulator was also purchased, modified and installed, and other components have needed replacement.

The Upgrade Specifications required a third amplifier, or alternatively, the first amplifier would be double-passed through a spatial filter to keep the beam clean. Neither option has been invoked, yet the laser has achieved its overall goal of 250mJ per shot at 532nm when everything is working properly.

MASTER RANGING CONTROL SYSTEM (MRCS) : Replaced the LRC. It is based on EPLD chips, and sets windows and gates, controls T/R rotation and laser firing, manages all clock and epoch timing functions, and contains a full range of test and simulation facilities. The MRCS communicates extensively with the Hewlett Packard A900 1000-series minicomputer as shown in figure 5.

50 MHZ MULTIPLIER : The MRCS operates at 50MHz, so a box was provided to multiply up the 10 MHz output from the Oscilloquartz 2200 crystal.

EPOCH TIMING SYSTEM : The basic philosophy of 'epoch' event timing has been retained, and is accomplished by the MRCS Clock down to 20ns with EOS-modified LeCroy 2229A TDC verniers providing fine resolution. The intermediate 4202A TDC units are no longer necessary, and only one 2229A TDC is needed on each of the start diode and MCP lines. Each of the 8 channels of a 2229A TDC has a resolution of 25ps (nominal), the average giving 10ps (typical) resolution and precision.

The scale units (ns/count) of the verniers can be calibrated in three ways:

- . Programmable delay lines within the MRCS;
- . LeCroy 4202A TDC verniers, assumed accurate;
- . Optical delay line. In a pseudo-ranging operation, part of a transmitted laser pulse is reflected from the feedback wedge in the T/R Assembly and directed to a retroreflector which slides along a calibrated optical rail, thence back through the wedge to the MCP (see figure 2). The change in TDC reading is then related to change in retroreflector position.

The average offset of each vernier with respect to the first vernier is calibrated daily by injecting a sequence of simulated laser pulses generated within the MRCS into all the verniers.

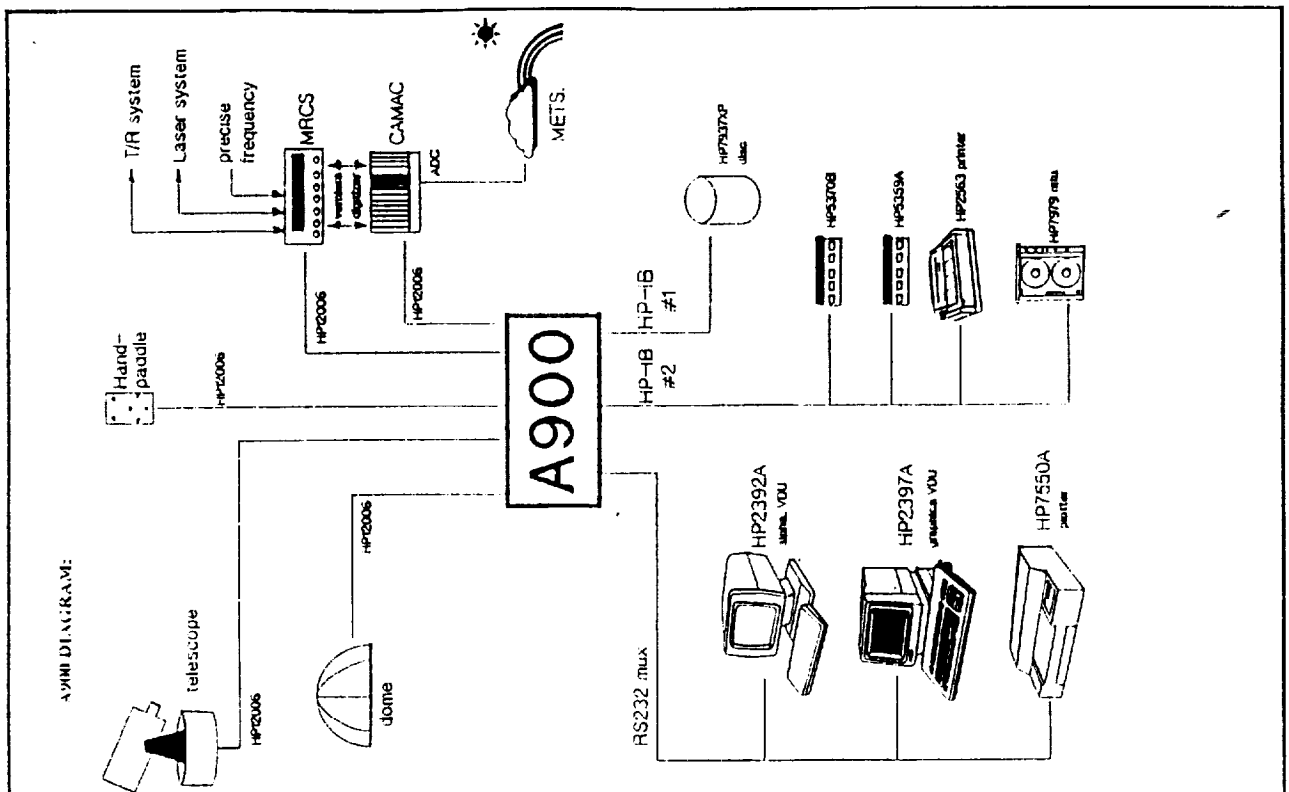


Figure 5: EOS Laser Ranging System. (EOS Operations Manual,V2.0)

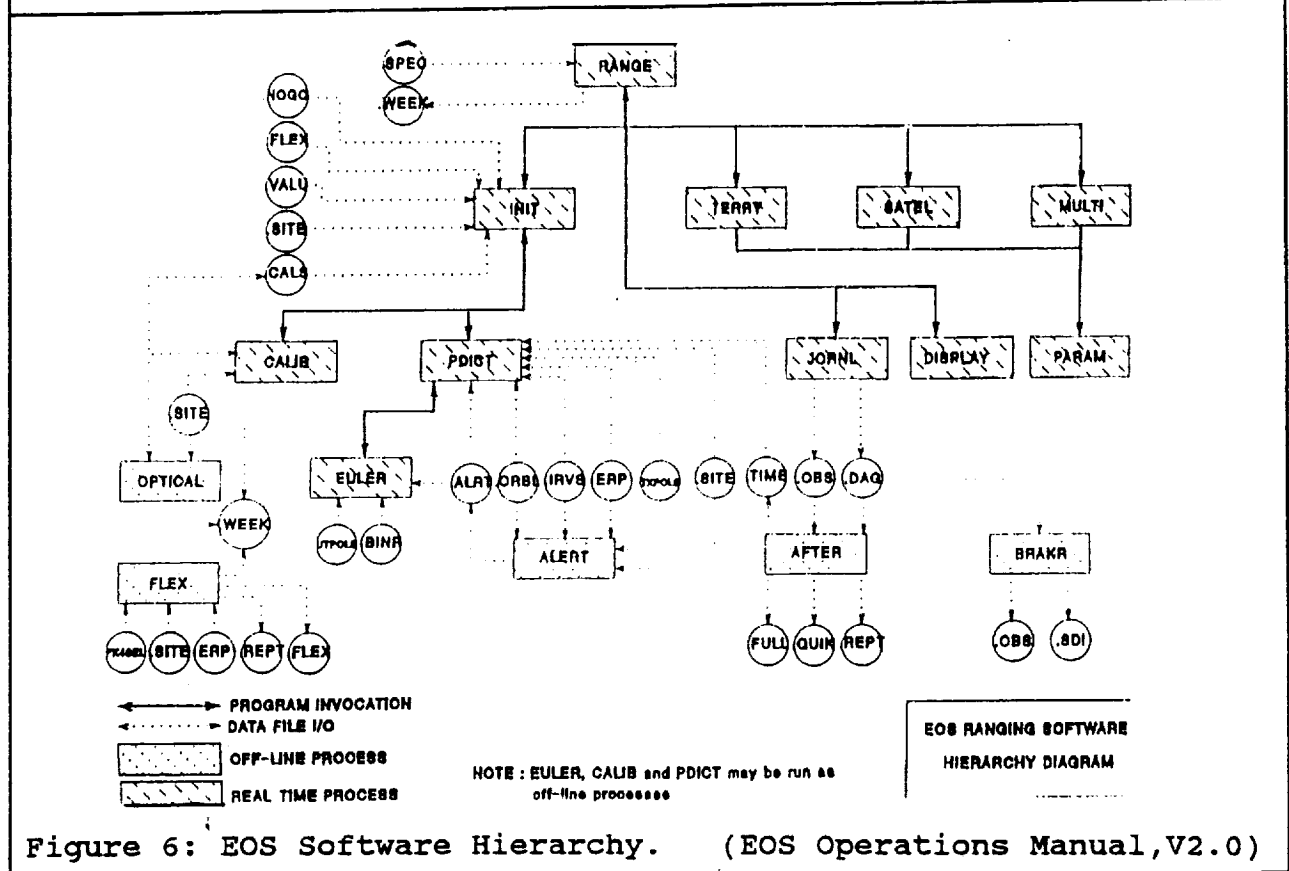


Figure 6: EOS Software Hierarchy. (EOS Operations Manual,V2.0)

RECEIVE ENERGY MONITOR : The previous system based on a LeCroy 2249A ADC has been retained, with hardware gating as above. The EOS software contains an option for automatic gating.

DISCRIMINATOR : As before, Tennelec 454 CFD units are used. EOS has experimented extensively with high-speed comparator chips, delay lines and 'cascade' configurations, but to date Orroral prefers to use unmodified single channels. The upgrade has also provided several potentially useful features for establishing the Z-walk on each channel, such as the PLZT 'wobbulator' and software, which are still being evaluated.

OPERATING SOFTWARE : The upgrade software provided, which is summarised in figure 6, includes mount modelling observations and analysis, pass predictions from receipt of IRV/ORBEL files, revamped EULER and IRVINT, ranging operations, post-processing to generation of normal point, full-rate data and time bias files, timing system calibration, file repair, diagnostic and reporting software. Source code was not included. The original software release was designed to apply 'generically' to all EOS systems; it has required considerable tailoring to Orroral's specific configurations, peculiarities, environment and requirements and has necessitated considerable re-education from an entrenched laser ranging 'culture'. Orroral prefers to use its own post-processing software, modified from the Natmap software to handle the new file structures.

Each interface driver is accompanied by a program demonstrating all its calls and providing extensive diagnostic and simulation capabilities. They cover CAMAC, MRCS, MPACS, PADDLE and DOME.

Ranging operations are built around three separate programs that handle ground targets, satellites out to about 70ms two-way range, and 'multiple shots in flight' targets such as ETALON and the moon, respectively.

SYSTEM CALIBRATION : To date, the same methods for real-time internal calibration and ground target ranging have been used as were used during 1987-91. The 'Table Target' on the Coude Table has been tested inconclusively; its signal strengths are expected to be controllable much better than those from the spider retros.

#### 4. Laser Performance

An assessment was performed in April-May 1991 by Dr Barry Luther-Davies of the Laser Physics Centre, Australian National University. The results and many quotations given below are taken from his report (Luther-Davies, 1991). The upgrade to an active/active oscillator and high-efficiency simmered heads has clearly provided very satisfactory performance.

PULSE DURATION : Output from the Second Harmonic Generator was measured using a Hadland Photonics IMACON 500 S20 streak camera

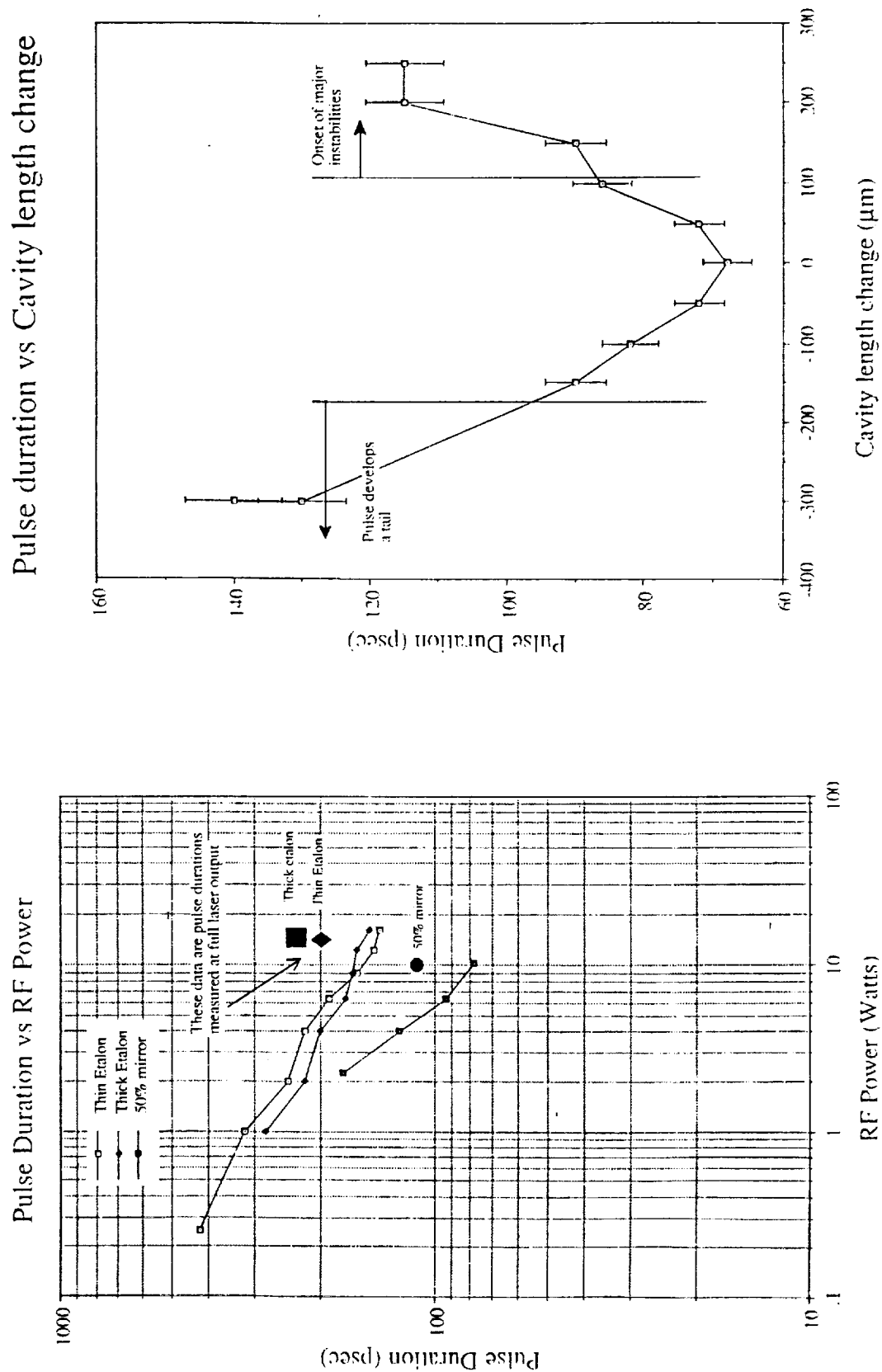


Figure 7: Active-active laser pulse duration- (a) vs RF power to AOM; (b) vs cavity length change. (Luther-Davies, 1991)

whose negatives were digitized with a CCD camera. Three different oscillator output reflectors were tested: a "thin" (3mm) Quantel etalon, a "thick" (6mm) Quantel etalon, and a 50% reflecting dielectric mirror. Pulse durations were measured as functions of RF drive power level to the AOM (figure 7(a)) and of cavity length (50% mirror only - figure 7(b)).

Minimum pulse durations at maximum appropriate RF drive power and full laser power were:

with 50% mirror : 110 +/- 5 ps  
 with thin etalon : 200 +/- 10 ps  
 with thick etalon : 240 +/- 12 ps.

The 50% mirror was subsequently adopted for normal use, and it was concluded that the oscillator is relatively insensitive to thermal expansion, +/- 5°C on a steel base being tolerable.

LASER OUTPUT ENERGY : Measured with a Scientech volume absorbing calorimeter, with the laser firing at 10 p.p.s. The results are summarised in Table 1. Two settings of the quarter-wave plate between the first and final amplifiers were used, with about a five degree rotation between the settings, to demonstrate the effect of thermally induced birefringence in the amplifiers.

**TABLE 1 : Orroral Average Laser Output Energy**

Position	Energy (mJ)	Comments
Oscillator,pre-lase	0.8	Osc.voltage 1660,RF drive 9.5W
Oscillator,full-train	5.56	Includes pre-lase, 4 pulses
Pulse slicer	1.1	Main pulse switched
Final amplifier, IR	>226.0	Amp.voltage 1420
SHG, green	> 56.0	Amp.voltage 1420, 1/4 wave "1"
SHG, green	> 67.0	Amp.voltage 1420, 1/4 wave "2"
SHG, green	>113.0	Amp.voltage 1570, 1/4 wave "2"

STABILITY : Output power stability was measured at 10 p.p.s. using the Scientech calorimeter or a silicon photodiode as appropriate, connected to a Hewlett Packard chart recorder. The results are given in Table 2. RMS jitter would be 3-4 times smaller than the peak-to-peak values quoted.

**TABLE 2 : Short-term Stability of Orroral Active/Active Laser**

Position	Av.Power (mW@10pps)	Jitter (p-p,%)	Period (mins)	Detector
Oscillator,full train	60	+/- 0.8	15	Calorimeter
Pulse slicer	11	1.4	15	Calorimeter
Pulse slicer	11	0.7	2	Photodiode (integrated)
Pulse slicer	11	0.8	120 shots	Photodiode (single shots)
Final amplifier,IR	2290	1.2	5	Photodiode (integrated)
Final amplifier,IR	2290	1.6	15	Calorimeter
SHG,green	600	2.0	15	Calorimeter

Worst-case RMS instability lower than 0.5% is inferred.

During these tests, over 100,000 shots were fired and no laser misfires were observed, nor was evidence seen of failure of the mode locking system to generate stable bandwidth limited pulses when the oscillator was correctly aligned.

**BEAM PROFILES** : The shape of the 532nm output pulse at 1 metre from the SHG was measured with a Pulnix CCD camera. The profiles in figure 8 were obtained: (a) at 40mJ average green energy, at which the beam is quite uniform; (b) at 80mJ, showing a four lobe structure and decreased diameter due to thermal lensing; and (c) at 113mJ with the quarter-wave plate rotated about 5° to emphasise the cross-like pattern caused by thermally induced birefringence in the amplifiers which in turn causes a spatially dependent depolarization of the beam and a variation of the frequency doubling efficiency across it.

## 5. Timing System Performance

Dr Ben Greene of EOS optimised the 2229A verniers of the epoch timing system in March 1992, and by means of pulses generated internally by the MRCS to simulate start diode and spider retro calibration returns, assessed their stability independently of the influences of MCP, discriminator and signal strength. The results of a 36 minute run where the data is binned in 30 second normal points of approximately 300 simulated shots each, are shown in figure 9. RMS about the mean was 6.2ps (0.93mm), which thus represents the intrinsic precision limit of the system during a LAGEOS pass.

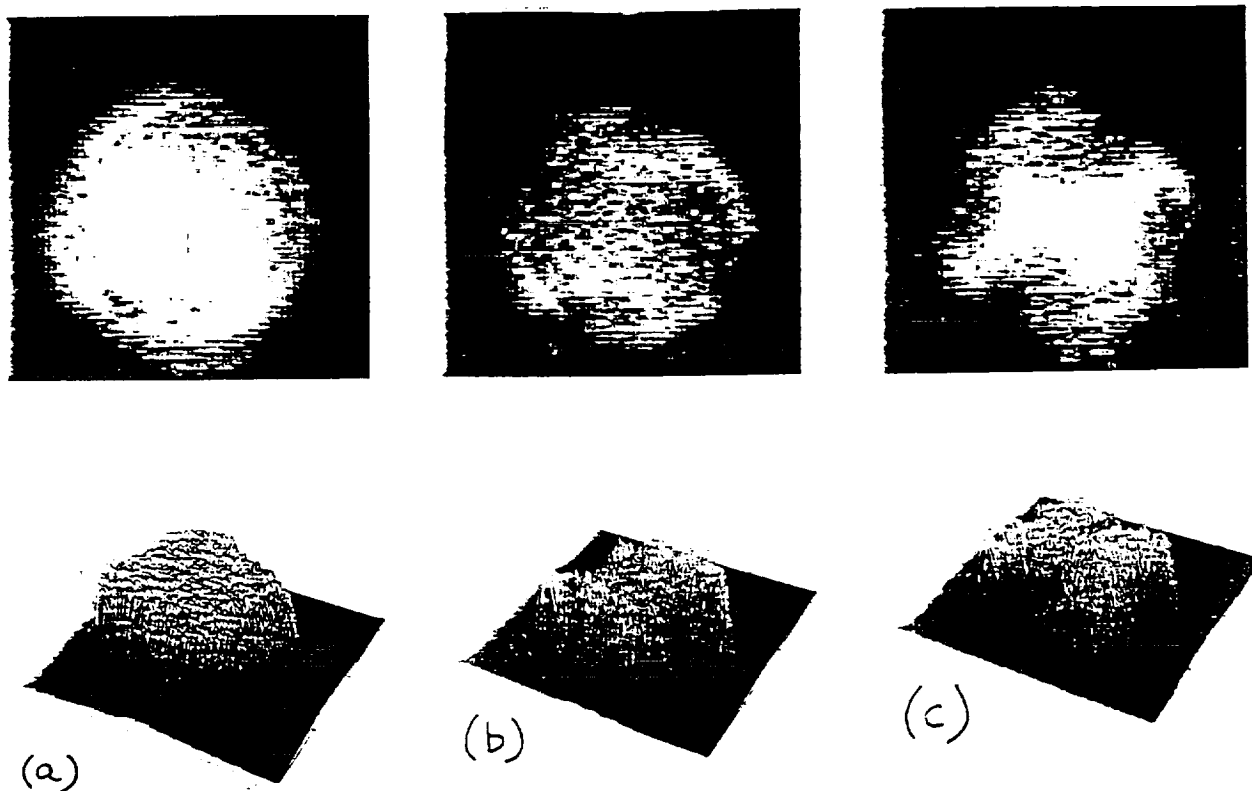


Figure 8: Laser beam profiles, 532nm green output 1m from SHG-  
(a) 40mJ/pulse in the green; (b) 80mJ/pulse green;  
(c) 113mJ/pulse green, quarter-wave plate rotated  $5^\circ$ .  
(Luther-Davies, 1991)

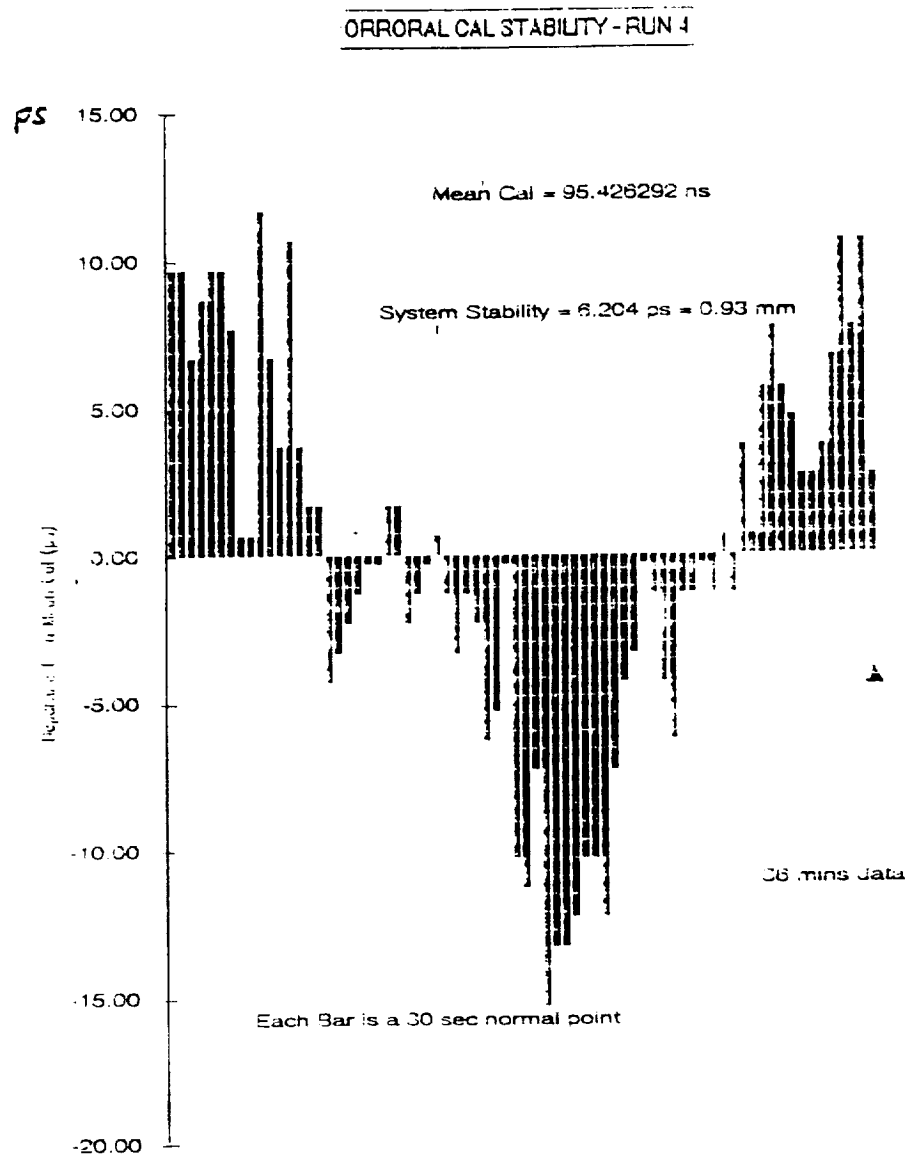


Figure 9: Timing system stability- residuals from mean of 36 minutes of simulated internal calibration data, binned at 30 second intervals (300 shots).



A systematic variation visible in figure 9 may be due to temperature variations in the CAMAC modules. The residuals from a 20 minute run were more random, with RMS 2.4ps (0.36mm).

An estimate of long-term stability is obtained from the daily calibration of the relative delay between verniers. In a 50 day period analysed during which the vernier scale units (ps/count) were held fixed at their values determined at the start of the period, the RMS variation of the delay difference between the two units actually used in ranging was 6.6ps (1.0mm).

It is thus evident that the precision and stability of the system, given perfect discriminator outputs, are 1mm or better. Because range calculations necessarily involve only vernier differences, this value also represents the accuracy limit of the system.

Data on the optical rail method of timing system calibration in situ at Orroral has not been obtained.

## 6. Pass Productivity

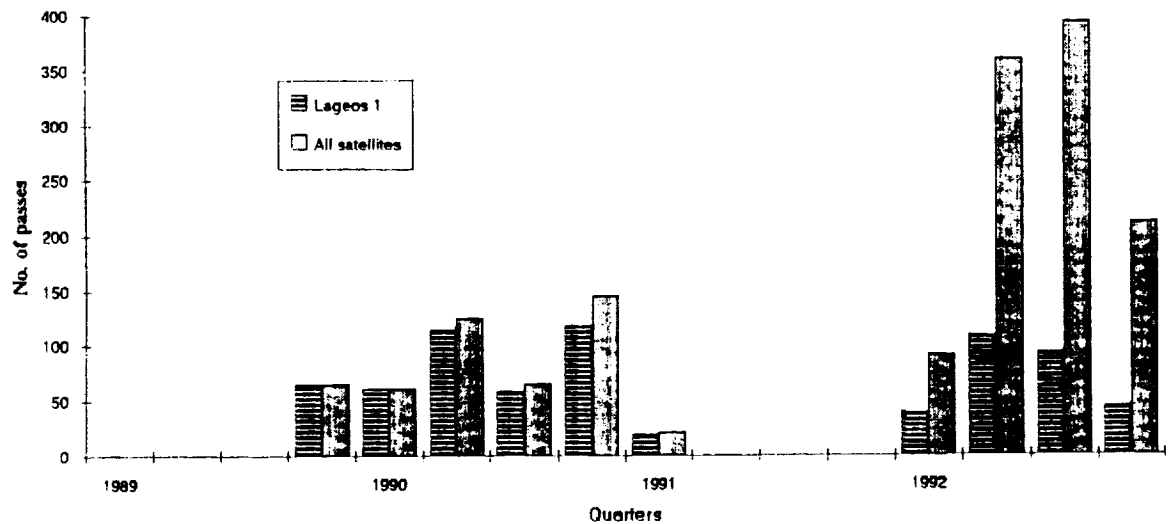
In figure 10(a), the growth in the number of passes acquired per quarter as a result of the upgrade is demonstrated. Prior to March 1991, only LAGEOS I and ETALON I & II (from June 1990) were observable. With the upgrade, STARLETTE, AJISAI and ERS-1 were immediately acquirable, with TOPEX/POSIDON and LAGEOS II being added in the second half of 1992. It is notable that the upgraded Orroral system was the first station to get returns from LAGEOS II, on 24 October. Monthly statistics for January to October 1992 are given in figure 10(b).

An unexpected consequence of the upgrade is that, in view of the enormous increase in number of passes available and the far greater reliability of the upgraded segments of the OIRS, more operational staff are needed in spite of greater system efficiency, and more technical staff are needed to maintain the other segments and bring them to an equal state of reliability and efficiency.

## 7. System Precision

The evolution of single-shot precision estimates for LAGEOS I ranging from Orroral is shown in figure 11. The data prior to the upgrade come from analyses of full-rate data by Peter Dunn of STX, and from in-house analysis thereafter. The failure to achieve the upgrade's sub-centimetre potential is ascribed to deterioration in laser alignment leading to longer pulses, to the difficulties encountered in optimising the MCP-Discriminator combination, and to a clear dependence of delay upon signal strength. Every effort is made to equalise signal strength distributions from satellite returns, spider retro calcs and

### Orroral Pass Productivity



### Orroral Pass Productivity, 1992

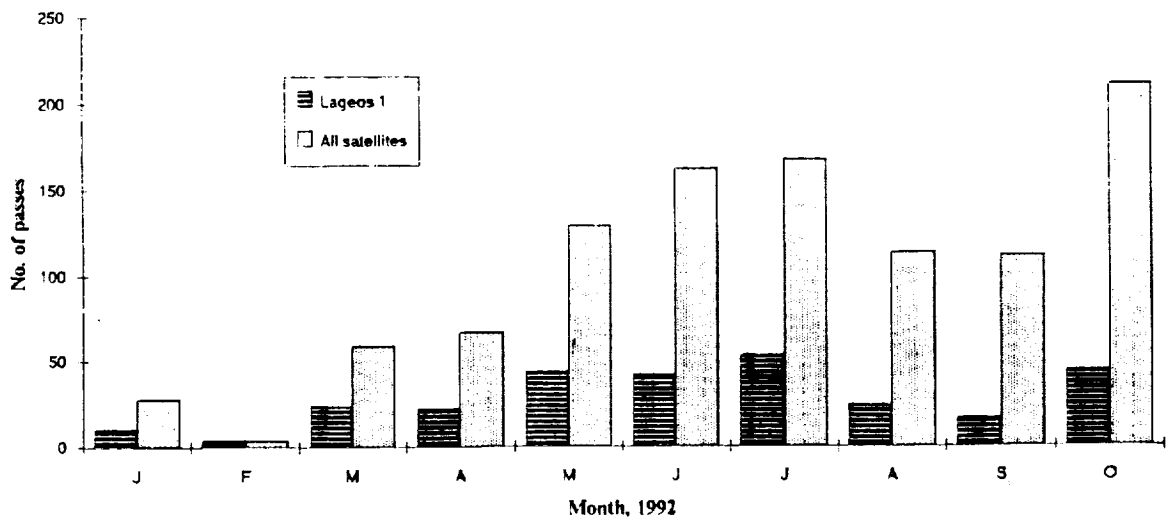


Figure 10: Number of usable passes from OLRs-  
(a) Quarterly, 1990-2; (b) Monthly, 1992.

ground target returns by judicious manipulation of the PLZT and telescope pointing, but it is difficult to do this in practice.

Ground target ranging offers more control over signal strengths. RMS values of 30ps (4.5mm) have been obtained in 5 minute sessions both for raw ground target returns uncorrected for refraction, and for internal calibrations. About 7mm is normal when everything is working properly, as illustrated for a good month in figure 13.

## 8. System Accuracy

Agreement with external standards is assessed two ways. It has not been possible to organise a co-location experiment.

COMPARISON WITH GROUND SURVEYS : The distance from the ground target retroreflector to all relevant instrumental points was measured by precise geodetic survey in late 1987 and repeated by independent methods and operators in late 1989. The formal one-sigma uncertainty of each survey was 3mm, and agreement was 8mm. The value adopted for the distance between the ground target and spider retro #1 from the more recent survey is 1141624mm.

The same distance is estimated from laser ranging by subtracting the calibration result from the raw range measurement, and applying a refraction correction based on EDM theory and meteorological readings (Rueger, 1980). No other corrections for delays inside the telescope are needed. Results for the first ten months of 1992 are displayed in figure 13. The extent to which improvements in signal strength control and laser pulse duration control will decrease the scatter and mean error, remains to be seen.

LAGEOS I RANGE BIAS : Figure 12 shows the range biases before and after the upgrade, relative to LAGEOS I orbits computed by the Center for Space Research, University of Texas (Eanes, 1992). There is evidence of a jump of between 20 and 60mm, but it is inconclusive as there could be contamination from orbit errors, station position errors, inclusion of data from 1991 when the upgrade was still being de-bugged, and truncation at May 1992. There has been no change in the constants and procedures used to reduce raw ranges to the adopted instrumental reference point (Coude mirror 7 - see figure 1), nor in the refraction algorithm applied to quick-look data. The Orroal reduction procedure is given in Appendix 1.

## 9. Telescope Pointing

MOUNT MODELLING : The analytical model developed previously for the Contraves mount and MPACS encoder system was specially coded into the generic EOS software. There are 10 parameters for each axis. It is solved from star observations by a non-linear process with observed encoder readings as the basic arguments. (The previous implementation by Natmap was solved as a linear

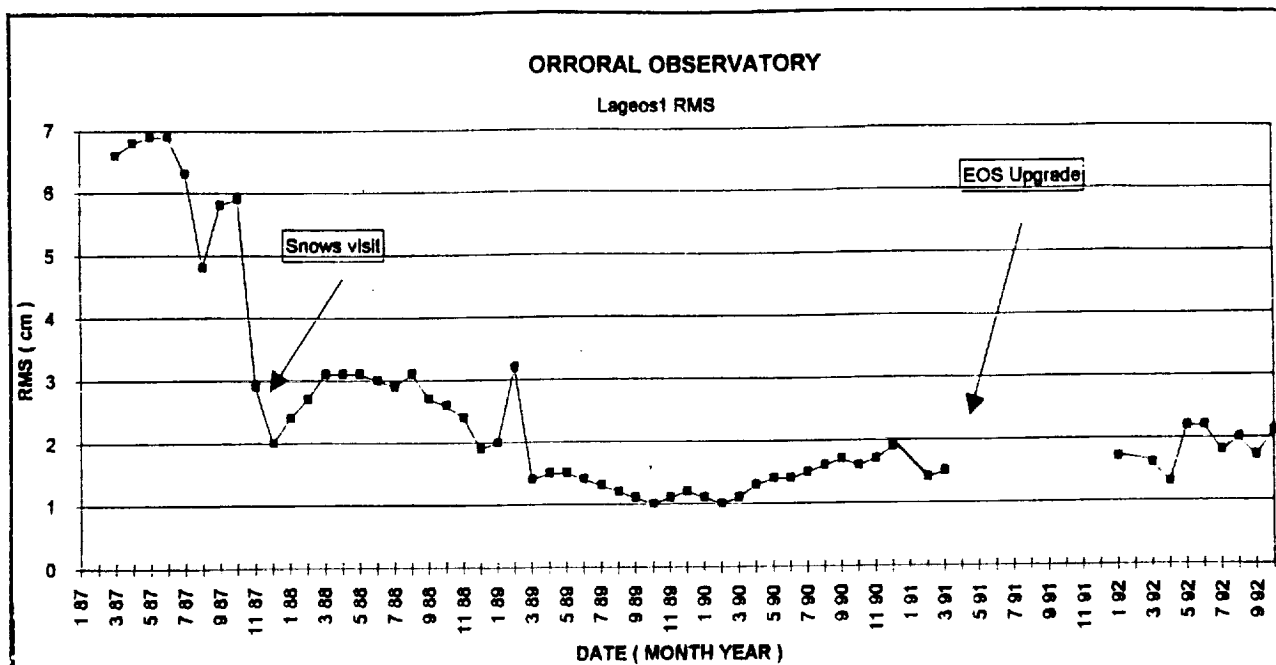


Figure 11: Monthly single-shot precision estimates for ranging to LAGEOS 1 from Orroral.

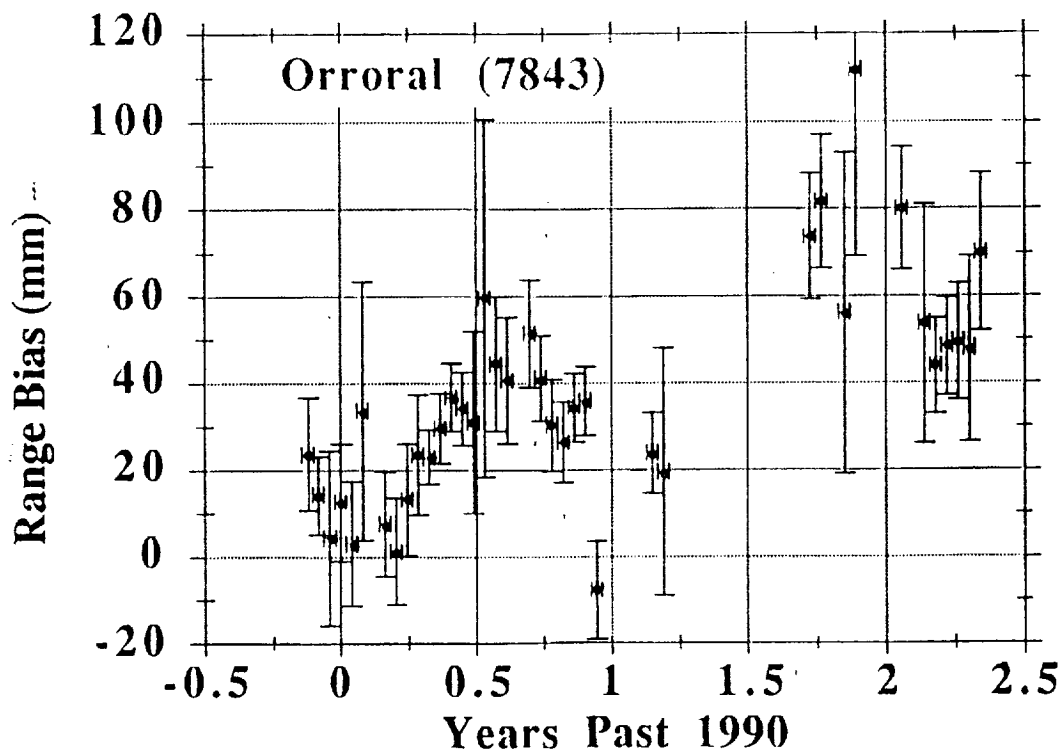


Figure 12: Two-week range bias estimates for ranging to LAGEOS I from Orroral, 1989-92. (Eanes, 1992)

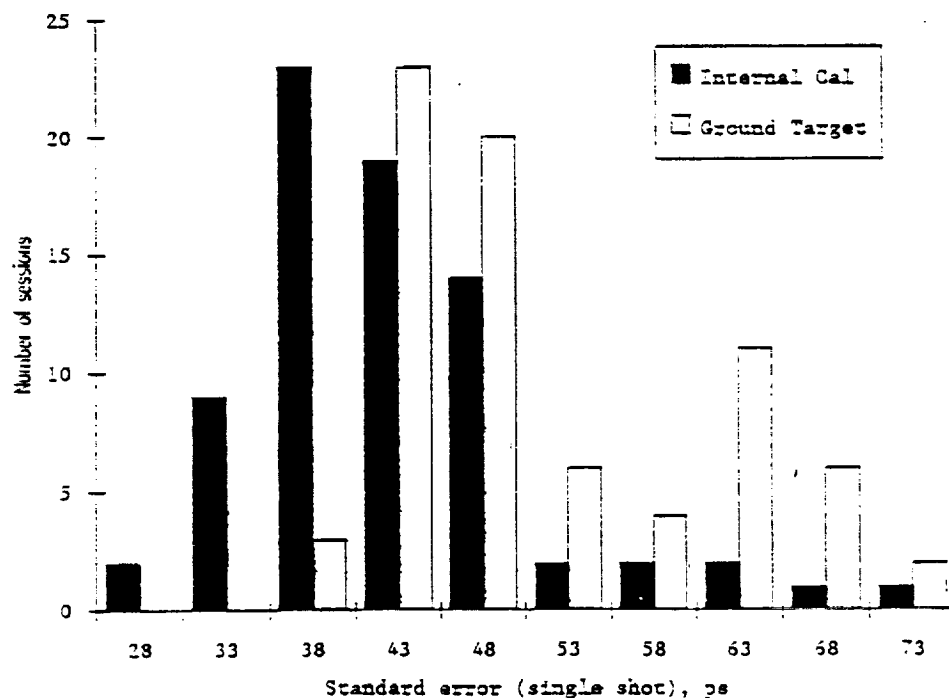


Figure 13: Raw ground target ranging precision (RMS) estimates, for sessions of about 5 minutes each in one month.

## ORRORAL GROUND TARGET RANGING

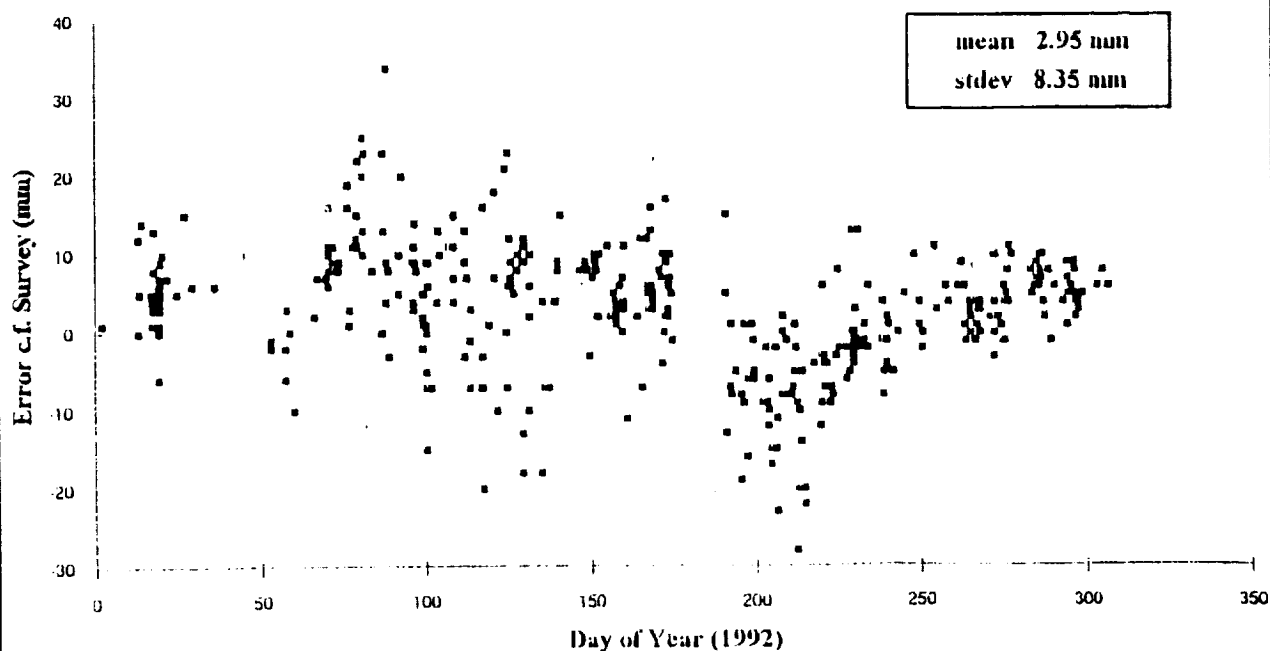


Figure 14: Comparison of reduced ground target ranging results in 1992 against adopted survey values.

model with ideal encoder readings as arguments.) The model is described in Appendix 2.

The star catalogue used is the FK4; previously, we used the homogeneous Perth 70 catalogue, which has a denser distribution.

Star observations are accomplished at the eyepiece at the Cassegrain focus. Star images are set, not on the eyepiece graticule centre but on the image of the coincident 'green spots' formed by returns from the two retroreflectors on the secondary mirror's spider vanes while the laser is firing. Thus the star is set in the direction in which the laser is actually transmitted, which automatically accounts for misalignments in the Coude path.

A feature of the upgraded system is that, between each repeat observation (normally 3) on each star, the telescope is driven off in a 'random' direction to minimise personal bias and any backlash. In other respects, observing speed and the star selection algorithm are inferior to those prior to the upgrade.

HANDPADDLES : For operator convenience in both star observations and ranging, the new handpaddles have thumbwheels to select the resolution of each 'click' of the paddle buttons. This feature has proven very useful.

POINTING ACCURACY AND PRECISION : The post-fit standard error of a full mount model solution from more than 20 stars is typically 3 seconds of arc. The upgrade's solution software does not provide the facility to assess numerically how closely the current model points to stars, so it has to be done at the eyepiece. Our estimate is 5-10 seconds of arc, which is also the typical pointing error to the more distant satellites.

## 10. Future Upgrades and Extensions

The EOS system is designed to be open-ended for future development. Post-upgrade projects already completed or in-hand include:

- . Semi-automatic ranging operations;
- . Variable speed dome automation;
- . Implementation of 'Table Cals';
- . Variable optical attenuation for satellite returns;
- . Optical design and fabrication for SPAD installation;
- . HP 9000-series Unix workstation for all displays, processing and graphical user interface, leaving the HP A-900 only for instrument control.

while projects made possible in the more distant future include:

- . Fully automatic ranging;
- . Converting laser to travelling-wave 'ring' design;
- . Operating at 40 shots per second;
- . Multi-colour ranging.

An important development not directly related to the upgrade but necessary for lunar ranging and desirable for optimum focussing on to a SPAD, is a new telescope secondary mirror which should be installed by July,1993. Its distance from the primary mirror was reduced by 4cm at the 1981 upgrade, which introduced enormous aberrations in the Ritchey-Chretien system because it was inadvertently assumed to be a true Cassegrain at the time (see,e.g.Schroeder,1987). A new optical prescription has been calculated which retains the existing primary mirror, matching assembly and tailpiece optics, reduces the inter-vertex distance by a further 4.5cm, eliminates coma and spherical aberration from the telescope, and reduces them considerably in the matching lens assembly (James,1992).

The heavily aberrated field-of-view at the pinholes in the receiver assembly is essentially zero (James,1992). The layout of assemblies on the Coude Table is being studied, to bring the receiver optically closer to the Beam Expander, if possible, in order to increase the field-of-view somewhat.

## 11. Acknowledgements

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Special thanks to John Degnan for his patience waiting for this manuscript, and to Mark Elphick and Steve Cootes for their beautiful drawings and graphs.

## 12. References

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## APPENDIX 1 : CORRECTIONS TO LASER RANGING OBSERVATIONS

### Notation

r : Raw range measurement - time interval between start diode epoch and MCP satellite return epoch (2-way, ns)  
R : Reduced range from instrumental reference point (Coude mirror 7) to reflection point of target, influenced by atmospheric delay (2-way, ns)  
c : Internal calibration - time interval between start diode epoch and MCP spider retro cal epoch (2-way, ns)  
a : Excess path length traversed by satellite returns in T/R box over path traversed by internal cal returns (1-way, ns)  
h : Distance between spider retro and centre of telescope tertiary mirror, projected on to optical axis (1-way, ns)  
s : Distance between centre of telescope tertiary mirror and system instrumental reference point which is the nominal centre of Coude Mirror 7 (outside the North bearing) (ns)  
g : Angle subtended at Coude Mirror 7 by the separation between the telescope's inner (Y) and outer (X) axes (rad)  
A : Telescope azimuth (ideal, ie assumes all mount model terms are zero)  
E : Telescope elevation angle (ideal)  
X : Telescope outer axis angle - 0° W, 90° meridian, 180° E  
Y : Telescope inner axis angle - 0° N, 90° prime vert, 180° S

### Coordinate Transformations

$$\begin{aligned}\cos Y &= \cos E \cos A \\ \cos X \sin Y &= -\cos E \sin A \\ \sin X \sin Y &= \sin E\end{aligned}$$

$$\begin{aligned}Y &= \cos^{-1}(\cos E \cos A) \\ X &= \tan^{-1}(\sin E / (-\cos E \sin A))\end{aligned}$$

### Range Reduction

$$R = r - 2*[s*\cos(Y + g) - h] - [c + a]$$

It is left to the analysts to convert to one-way range and to apply refraction and centre-of-mass corrections.

### Numerical Values of Constants

s = 10.0389 ns (corresponding to 3.010 metres)  
g = 0.16624 rad (corresponding to 9.525 degrees, axis offset 495 mm)  
h = 8.9896 ns (corresponding to 2.695 metres)  
a = | 1.644 ns (satellite targets)  
| 0.000 ns (terrestrial targets)



## APPENDIX 2 : ORRORAL MOUNT MODEL

### Notation

$X$  : Encoder reading, actual, outer axis  
 $X_o$  : Encoder reading, ideal, outer axis  
 $Y$  : Encoder reading, actual, inner axis  
 $Y_o$  : Encoder reading, ideal, inner axis  
 $p$  :  $X_o - 90^\circ$  : zero at zenith  
 $q$  :  $Y_o - 90^\circ$  : zero at zenith  
 $c_i, i=1, \dots, 20$  : Solution coefficients of mount model, either axis  
 $f_i, i=1, \dots, 20$  : Mount model functions, either axis

### Linear Model

$$\begin{aligned}
 X &= X_o + c_1 f_1(p, q) + c_3 f_3(p, q) + c_5 f_5(p, q) + \dots \\
 Y &= Y_o + c_2 f_2(p, q) + c_4 f_4(p, q) + c_6 f_6(p, q) + \dots
 \end{aligned}$$

### Functions

i	Function $f_i(p, q)$	Description	Small Angle Expansion
<u>Outer axis (X)</u>			
1	1	X encoder zero point error	1
3	p	X encoder scale error	p
5	q	Cross scale error (empirical)	q
7	$1 - \cos p$	X encoder de-centering	$p^2/2$
9	$-\sin p \tan q$	Outer axis inclination error	pq
11	$1 - \sec q$	Optic axis non-perp to inner axis	$-q^2/2$
13	$p - \tan p$	Yoke (outer axis) flexure	$-p^3/3$
15	$\cos p \tan q - q$	Outer axis azimuth error	$-p^2q/2 + q^3/3$
17	$p - \sin p \sec q$	Telescope tube flexure (sin z)	$p^3/6 - pq^2/2$
19	$q - \tan q$	Non-orthogonality of axes	$-q^3/3$
<u>Inner Axis (Y)</u>			
2	1	Y encoder zero point error	1
4	q	Y encoder scale error	q
6	p	Cross scale error (empirical)	p
8	$1 - \cos q$	Y encoder de-centering	$q^2/2$
10	$\tan p \sin q$	Empirical	pq
12	$1 - \cos p$	Outer axis inclination error	$p^2/2$
14	$q - \cos p \sin q$	Telescope tube flexure (sin z)	$q^3/6 + p^2q/2$
16	$\tan p \cos q - p$	Empirical	$-pq^2/2 + p^3/6$
18	$\sin q - q$	Empirical	$-q^3/6$
20	$p - \sin p$	Outer axis azimuth error	$p^3/6$

Empirical terms were determined by residual analysis. Terms are ordered by small angle expansions around zenith which aids de-correlation of solution parameters especially with few stars.